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EVALUATION OF THE INFLUENCE OF LOAD RANDOMIZATION AND OF GROUND-AIR-GROUND CYCLES ON FATIGUE LIFE

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ERRATA

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Page 7: In figure 1 near the top right, the entry under Program 1 following the words "block size" should be corrected to read

$\approx$1800 cycles = 150 flights

instead of

$\approx$10,200 cycles = 125 flights

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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EVALUATION OF THE INFLUENCE OF LOAD RANDOMIZATION

AND OF GROUND-AIR-GROUND CYCLES ON FATIGUE LIFE

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SUMMARY

A1

A1 Variable-amplitude axial-load fatigue tests were conducted on 2024-T3 and 7075-T6 aluminum-alloy edge notched sheet specimens having a theoretical elastic stress concentration factor of 4. The load programs were designed to approximate a gust-load spectrum. The introduction of ground-air-ground cycles sharply reduced the fatigue life. The amount of the reduction in fatigue life was found to be influenced by ground-air-ground cycle range, relative frequency of occurrence of the ground-air-ground cycle, and the degree of load randomization present in the tests. Omitting small amplitude loads did not have an appreciable effect on fatigue life. A new programed variable-amplitude axial-load fatigue machine is described. Jump to p. 12

INTRODUCTION

Fatigue-induced catastrophic failures in commercial and military aircraft have caused a great deal of concern in recent years. The probability of such a failure has been reduced both by evaluation fatigue tests on prototype full-scale vehicles and by inspection of vehicles after periods of service. The frequency of the inspections and the primary locations within the structure to be inspected are in many cases a direct result of the evaluation test. It is, therefore, of primary importance that both the spectrum of loads and the method used to simulate the spectrum be carefully evaluated. The present investigation is concerned with the evaluation of the influence on fatigue life of several possible techniques for simulating a given load spectrum.

There are many techniques by which a continuous load spectrum can be simulated; these schemes vary in complexity from flight-by-flight programing of multiple load levels to single-level constant-amplitude tests. References 1 to 3 report variations in fatigue life obtained in variable-amplitude fatigue tests simulating either a gust-load history or a maneuver-load history. All the tests reported in references 1 to 3 used eight load levels to simulate the continuous load history; the cycles at each load level were applied in groups of identical cycles (block tests).

In the present investigation, the effect on fatigue life of various types of load randomization was evaluated. In addition, the effect on fatigue life

of introducing ground-air-ground cycles was evaluated under a variety of combinations of load randomizations, materials, and ground-air-ground cycle magnitudes, and relative frequency of occurrence.

A new testing device capable of applying 55 discrete load levels in any sequence, by utilizing punched cards, was developed for this study. A brief description of the device is included.

The units used for the physical quantities used herein are given in the U.S. Customary Units and parenthetically in the International Systems of Units, SI (ref. 4). An appendix is included to explain the relationships between these two systems of units.

SYMBOLS

S_{alt} alternating stress amplitude, ksi $\left(MN/m^2\right)$

S_d stress produced by design limit load, ksi $\left(MN/m^2\right)$

S_{mean} mean stress, ksi $\left(MN/m^2\right)$

V_i discrete gust velocity, fps (m/s)

S_{1g} stress produced in straight and level flight, ksi $\left(MN/m^2\right)$

n_i number of cycles applied at a level i

N_i number of cycles necessary to produce failure at stress level i

R ratio of minimum stress to maximum stress

Subscript:

GAG ground-air-ground

TEST PROCEDURES

Specimens

The edge notched specimen configuration (fig. 1) used for this investigation had a Neuber theoretical elastic stress concentration factor of 4 (see ref. 5). This configuration is the same as that used in investigations of references 1 to 3.

Material for specimens was part of a stock of commercial 0.090-inch (0.0023-m) thick 2024-T3 and 7075-T6 aluminum alloy retained at the Langley

Research Center for fatigue tests. Sheet layouts for these stock materials are presented in reference 6. Material properties are given in reference 7, and selected tensile properties for these stock materials are given in table I.

A specimen numbering system has been established (see ref. 1) which identifies the specimen as to material, sheet number, and location within the sheet. Take for example, specimen B93N2-6 where B indicates the material (7075-T6), 93 indicates that the specimen was cut from sheet number 93, N2 indicates the position within the sheet from which the material blank was taken, and 6 indicates the position within the material blank from which the specimen blank was taken.

Specimen dimensions are shown in figure 1. The rolled surfaces were left in the as-received condition and the longitudinal surfaces were machined and notched in both edges. The notch radius was formed by drilling a hole. Residual machining stresses were minimized by first drilling with a small drill and then gradually increasing drill sizes (increment in diameter is 0.003 inch (0.076 mm)) until the proper radius was obtained. For consistency, drills were not used more than four times before being resharpened or replaced. The notch was completed by slotting with a $\frac{3}{32}$-inch (2.4-mm) milling tool. Ten specimens were machined simultaneously.

Burrs left in the machining process were removed by holding the specimen lightly against a rotating cone of 00 grade steel wool. All specimens were inspected and only those free of surface blemishes in and near the notches were tested.

Machines

Three programed servohydraulic machines were used in this investigation. A typical "block" diagram of one of the machines is shown in figure 2. The loading frame has a nominal capacity of ±20,000 pounds (±88,960 N) in axial load. Cycling rates up to 7 cps (7 Hz) can be obtained depending on the load range. The important features of this programed load fatigue machine are: (1) 55 discrete load levels, each identified by its own code, can be preset to any value between zero and full scale; (2) any type of load history defined by as many as 55 discrete load levels can be programed in any arbitrary sequence by using punched cards; and (3) a high degree of load accuracy is maintained throughout a test.

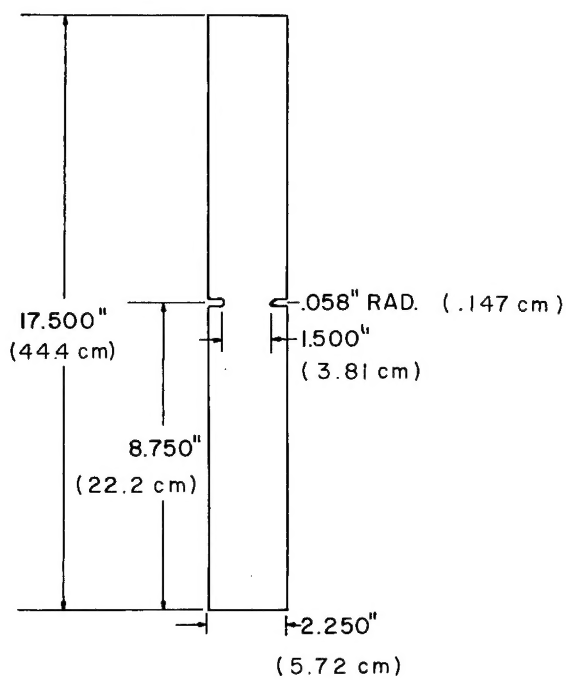


Figure 1.- Details of sheet specimen.

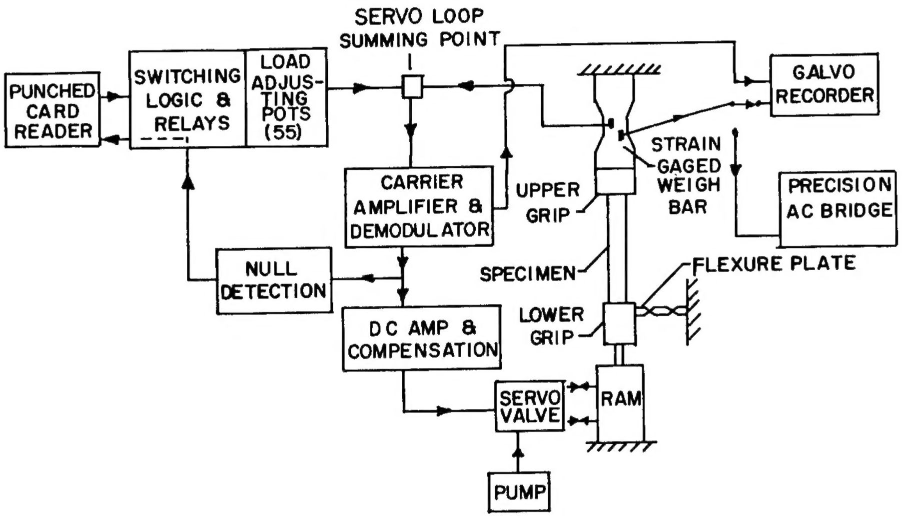


Figure 2.- Block diagram of axial-load programed fatigue machine.

In operation, the card reader transmits coded load information to the switching logic. Upon receipt of this information, the switching logic performs selected functional checks and then switches the desired discrete load signal (from a preset 10-turn potentiometer) into the servoloop summing point. The combined voltage from the summing point is fed into the carrier amplifier where the incoming voltage is compared with a reference voltage to determine the magnitude and polarity of the signal sent to the d-c amplifier. The d-c amplifier uses this signal to cause the servovalve to direct oil to the appropriate side of the ram, thus loading the specimen and thereby changing the output from the strain-gage bridge. As the load applied to the specimen approaches the desired load, the flow is proportionately slowed so that the applied load approaches the desired load asymptotically. When the applied load equals the desired load (within adjustable limits), a signal is generated which commands the reader to transmit the next piece of load information to the switching logic.

A continuous check for malfunction in several portions of the load system is provided. For example: specimen failure (complete separation of the specimen), the detection of an error in the switching logic functional checks, or loss of command signal to the servovalve cause an immediate stop in oil flow by deenergizing a solenoid-controlled flow valve.

Loads are monitored by either a galvonometer recorder or a null-indicating a-c bridge. The recorder is used to scan for extraneous loads, whereas the a-c bridge is used for static load measurements and to check system damping. The whole system is calibrated periodically and static indication is repeatable to 0.1 percent of full scale. True load accuracy is estimated to be within ±0.2 percent of full scale.

Load Spectrum Simulation

Load statistics.- Loads in transport aircraft due to atmospheric gusts were assumed to have a distribution of frequencies as given in reference 8. Gust velocities were converted to stresses on the assumption that stress is directly proportional to gust velocity and that a 30-fps (9.144-m/s) gust produced a stress equal to the stress at design limit load. Thus, alternating-stress amplitudes were computed from the simple relation

$$S_{alt} = \left(S_d - S_{1g}\right)\frac{V_i}{30} \tag{1}$$

Positive gusts were represented by positive loads and negative gusts were represented by negative loads with respect to the S_{1g} reference. Therefore, a positive gust representation started at S_{1g}, went to the desired value, and returned to S_{1g}; similarly, a negative gust started at S_{1g}, went to the desired value, and returned to S_{1g}. A gust-load cycle was comprised of one positive gust and one negative gust. Positive and negative gusts of a given velocity were assumed to occur with equal frequency.

Block test.- The continuous-load spectra were represented in most cases by eight-step loading schedules. The discrete values of stress were obtained by numerically integrating the damage due to a band of stresses and then selecting a stress level which gave the same theoretical damage when applied for the same number of cycles. Block size was determined by making the summation of cycle ratios $\sum n/N$ for one block approximately 0.1. The numerical integration process is explained in detail in reference 1. The eight-step loading schedules (including variations), developed by using the numerical integration process applicable to this investigation, are given in table II, and are taken from reference 1. For block tests, all the cycles at a given load level were applied in a continuous sequence before proceeding to the next load level. The sequence of load levels within each block was randomized in accordance with a schedule taken from a table of random numbers. A different randomization was used for each of the first 20 blocks, after which the random blocks were repeated starting with the first block.

Random tests.- To evaluate the possible effect of applying a given set of loads in a random sequence as compared with blocks of cycles having the same frequency of occurrence, the individual load cycles were programed in a random sequence. Using reference 9 as a guide, the random sequence was obtained by generating six-digit random numbers in high-speed computers. This method has a repetitive period of 5×10^8. The range of generated numbers between 0 and 10^6 was divided into segments of numbers, with each segment coded to represent a given load level. The size of each segment was determined by the relative frequency of occurrence of the load level as determined from equation (1). Thus, by varying the size of the segments, the cumulative frequency distribution of the load levels was shaped.

The following basic randomizations were developed for this investigation:

1. Random cycle: Each positive half cycle (positive gust) was followed by negative half cycle of equal magnitude (negative gust).

2. Random half cycle, restrained: Each positive half cycle was followed by a negative half cycle which could be, but generally was not, of equal magnitude.

3. Random half cycle, unrestrained: No restrictions were placed on the occurrence of positive or negative half cycles.

Test Load Programs

The following load programs and subprograms were used in this investigation to conduct fatigue tests to evaluate the possible effects on fatigue life of load randomization and of insertion of ground-air-ground cycles. A schematic representation of each of the load programs and subprograms is shown in figure 3.

Ground-air-ground spacing was determined with the aid of VGH data such as that presented in reference 10. It is beyond the scope of this paper to present the complete analysis. However, it can be shown that for the cumulative frequency distribution used, the lowest load level will be equaled or exceeded approximately 68 times per flight on the average and that the second lowest load level will be equaled or exceeded approximately 12 times per flight on the average. In the random tests, the loads were applied on a flight-by-flight basis, therefore in tests having all eight-gust load levels, the GAG cycle was inserted once for every 68 positive half cycles; whereas, in tests in which the lowest gust-load level was omitted the GAG cycles were inserted every 12 positive half cycles.

The earlier tests in this series were conducted by using semiautomatic load controls (refs. 1 to 3). It was decided that a check was necessary to insure that a significant variation in life would not be obtained due to such parameters as machine differences, speed effect, or load accuracy. Consequently, a set of block tests was conducted in the new machines (automatic) for which the load schedule was identical to that used in earlier tests (semiautomatic). See reference 3.

Two series of tests were conducted to determine whether two assumptions made when developing the random-cycle programs were valid. The two assumptions in question were (1) that assigning load-level designations to ranges of generated numbers did not affect the randomness of the generated numbers, and (2) that the location of the highest load level (which occurred only once per test on the average) would not have a significant effect on the fatigue life.

For the series of tests used to evaluate assumption (1) random-cycle tests were conducted by using program 2(b) and modifications. The modifications consisted of starting at different points within the same random schedule. The loads for program 2(b) were punched into cards with a density of 34 cycles per

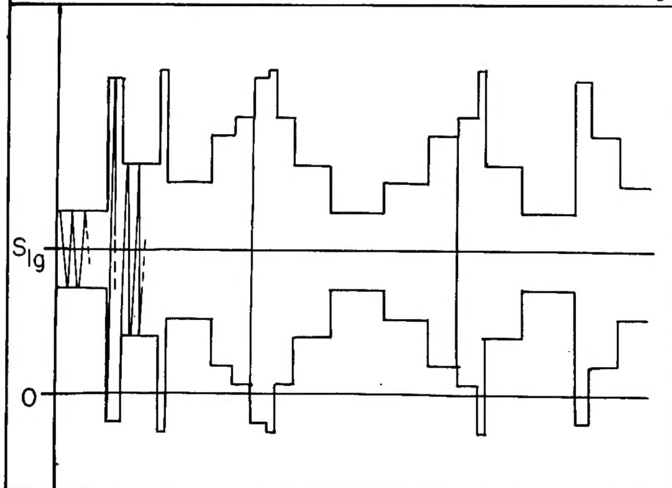
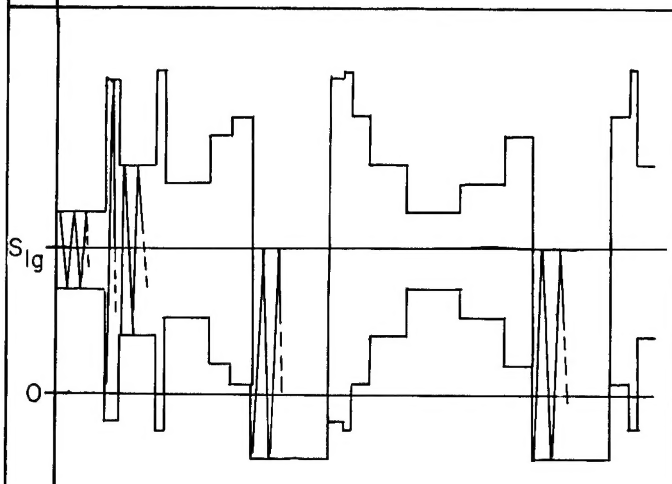
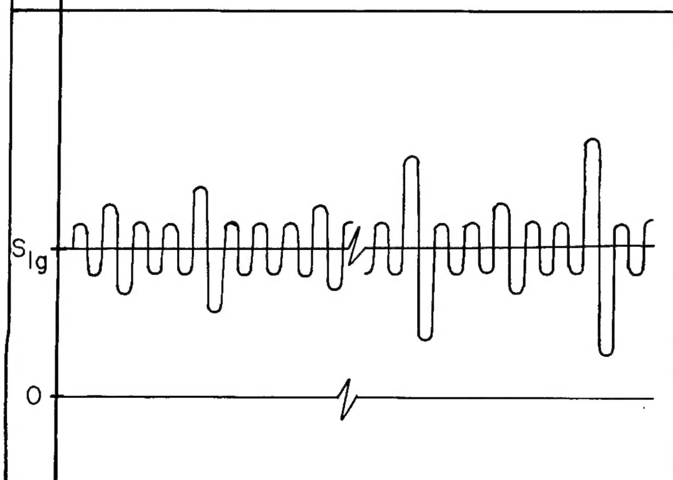
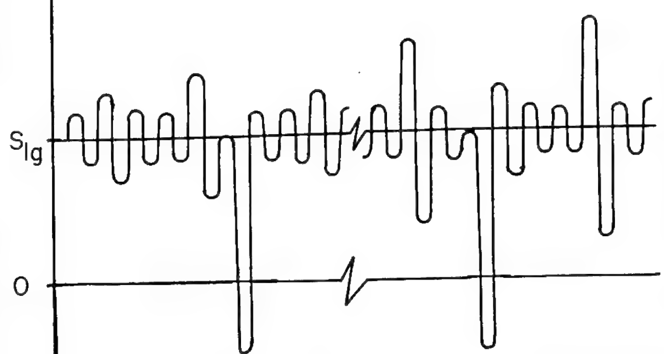
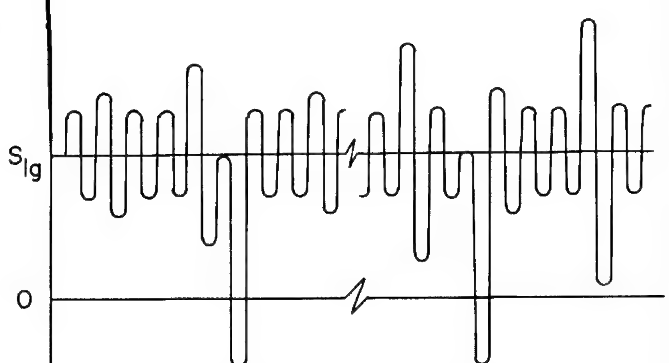
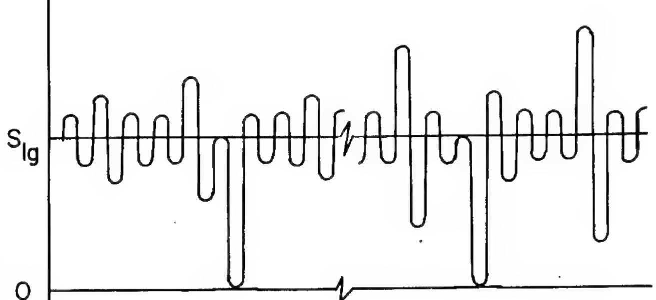
LOAD PROGRAM SCHEMATIC	REMARKS
7075-T6 Aluminum-alloy specimens; S_{1g}=20 ksi (137.8 MN/m²)	
	Program 1: Block; 7075-T6; S_{1g} = 20 ksi (137.8 MN/m²); step 1 omitted; block size ≈10,200 cycles = 125 flights. (Flights are used as a measure of life, see subsequent discussion.)
	Program 1(a): Same as program 1 except 125 ground-air-ground cycles inserted at the end of each block; ground-air-ground cycle range = S_{1g} to $-1/2S_{1g}$ (R_{GAG} = -1/2).
	Program 2: Random cycle; 7075-T6; S_{1g} = 20 ksi (137.8 MN/m²); 68 positive half cycles per flight.

Figure 3.- Schematic representation of load programs used.

<table>
<tr><th>LOAD PROGRAM SCHEMATIC</th><th>REMARKS</th></tr>
<tr><td>
</td><td>Program 2(a):

Same as program 2 except one ground-air-ground cycle was inserted per 68 positive half cycles; R_{GAG} = -1/2.</td></tr>
<tr><td>
</td><td>Program 2(b):

Same as program 2(a) except step 1 omitted; one ground-air-ground cycle was inserted per 12 positive half cycles; R_{GAG} = -1/2.</td></tr>
<tr><td>
</td><td>Program 2(c):

Same as program 2 except one ground-air-ground cycle was inserted per 68 positive half cycles; R_{GAG} = 0.</td></tr>
</table>

Figure 3.- Continued.

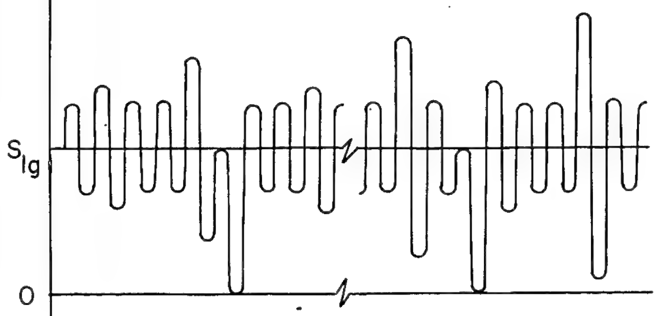
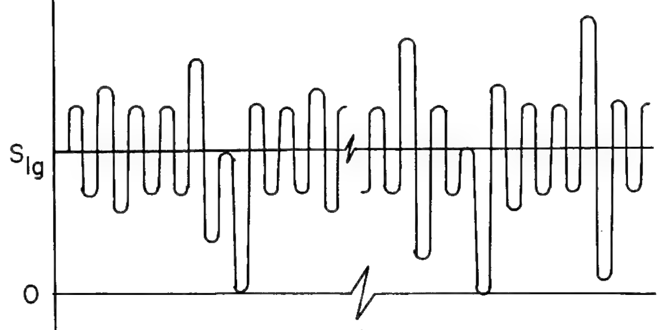
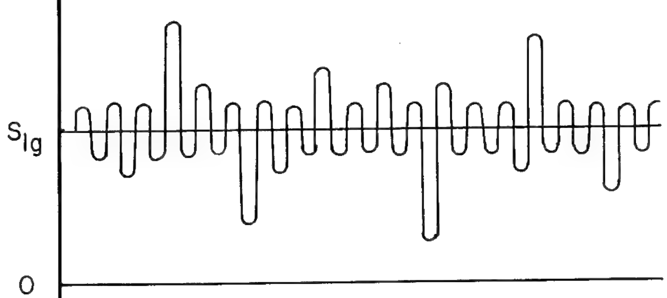
LOAD PROGRAM SCHEMATIC	REMARKS
	**Program 2(d):** Same as program 2(c) except step 1 omitted; one ground-air-ground cycle was inserted per 12 positive half cycles; R_{GAG} = 0.
	**Program 2(e):** Same as program 2(d) except one ground-air-ground cycle was inserted per 6 positive half cycles; R_{GAG} = 0.
	Program 3: Random half cycle, restrained; 7075-T6; S_{1g} = 20 ksi (137.8 MN/m^2), 68 positive half cycles per flight.

Figure 3.- Continued.

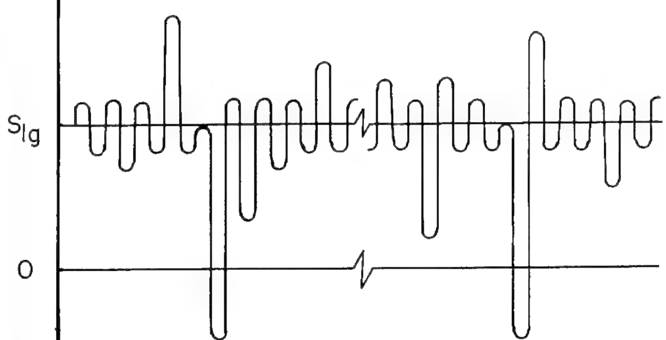
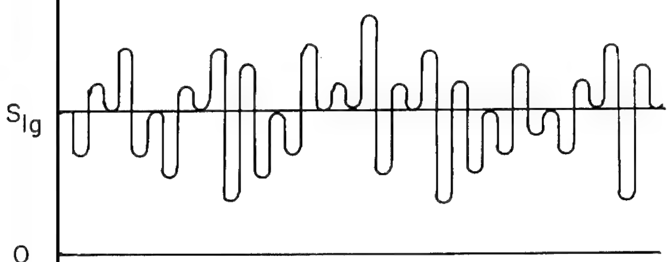
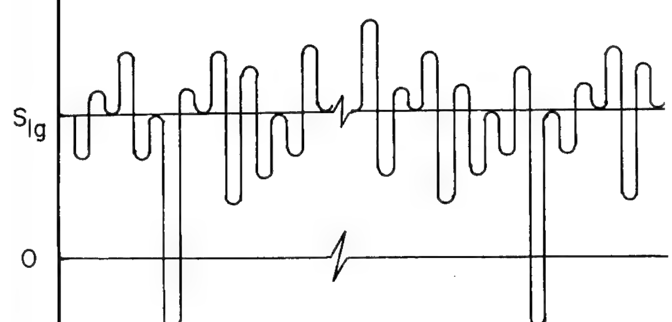
LOAD PROGRAM SCHEMATIC	REMARKS
	**Program 3(a):** Same as program 3 except one ground-air-ground cycle was inserted per 68 positive half cycles; $R_{GAG} = -1/2$.
	**Program 4:** Random half cycle, unrestrained; 7075-T6; S_{1g} = 20 ksi (137.8 MN/m^2); 68 positive half cycles per flight.
	**Program 4(a):** Same as program 4 except one ground-air-ground cycle was inserted per 68 positive half cycles; $R_{GAG} = -1/2$.

Figure 3.- Continued.

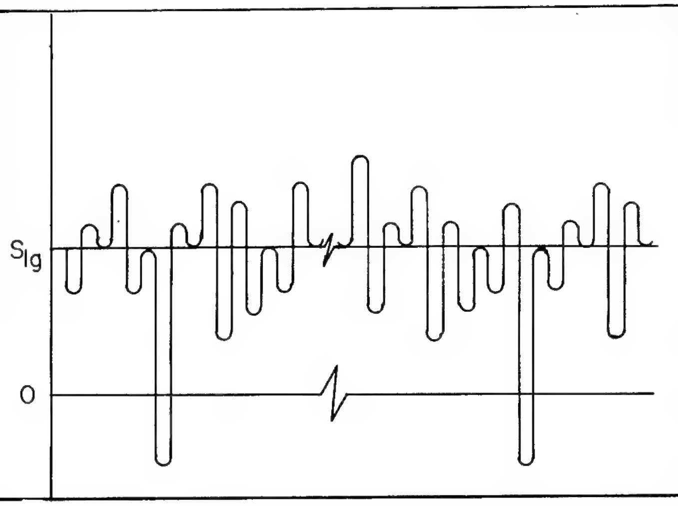
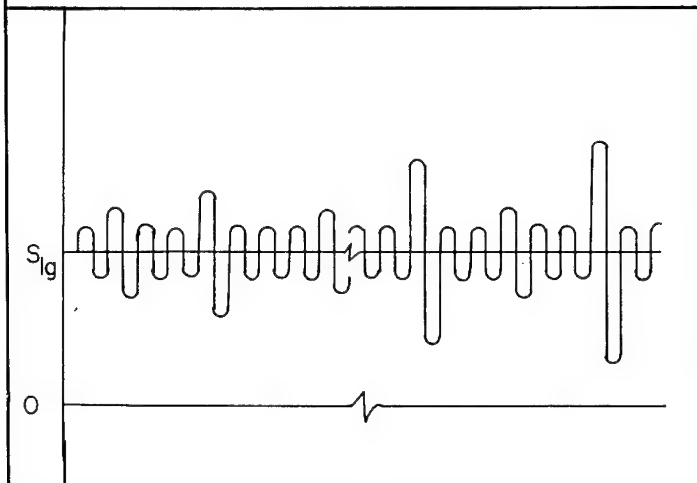
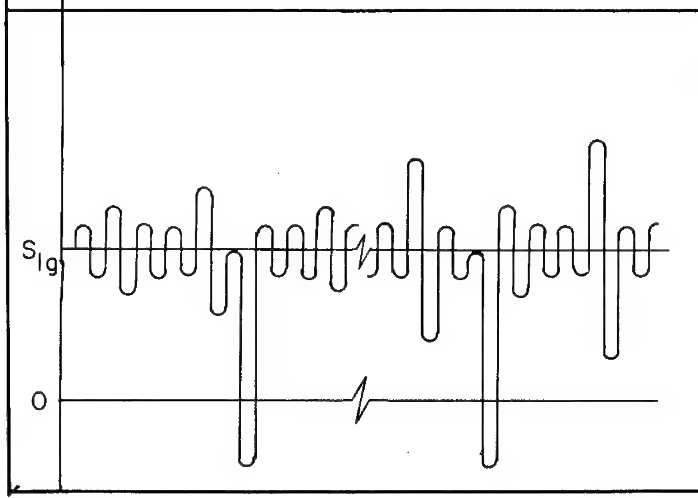
LOAD PROGRAM SCHEMATIC	REMARKS
	Program 4(b): Same as program 4 except one ground-air-ground cycle was inserted per 45 positive half cycles; R_{GAG} = -1/2.
2024-T3 Aluminum-alloy specimens; S_{1g} = 17.4 ksi (119.9 MN/m^2)	
	Program 5: Random cycle; 2024-T3; S_{1g} = 17.4 ksi (119.9 MN/m^2); 68 positive half cycles per flight.
	Program 5(a): Same as program 5 except one ground-air-ground cycle was inserted per 68 positive half cycles; R_{GAG} = -1/2.

Figure 3.- Concluded.

card. Approximately 2500 cards were used for this load program. Tests were then conducted starting at card 1, card 500, card 1000, and card 1500. It should be noted that the highest load level occurred only once during the program and was scheduled on card 1435.

The second assumption was evaluated by using block tests, program 1(b), in which the highest load level was scheduled on card 1445. For this series of tests, card 1445 was inserted at the following locations: (1) before card 1, (2) before card 250, (3) before card 700, (4) before card 1446 (normal location), and (5) before card 1800.

In order to compute a value of $\sum n/N$ for the ground-air-ground cycle, it was necessary in two cases (20 ksi (137.8 MN/m^2) to -10 ksi (-68.9 MN/m^2) for 7075-T6 aluminum alloy and 17.4 ksi (119.9 MN/m^2) to 8.7 ksi (-59.9 MN/m^2) for 2024-T3 aluminum alloy) to conduct constant-amplitude tests. For the third case, the life for the GAG cycle 20 ksi (137.8 MN/m^2) to 0 for 7075-T6 aluminum alloy was taken to be 50,000 cycles, based on an S-N curve for S_{mean} = 10 ksi (68.9 MN/m^2) in reference 1.

RESULTS

Test Data

Constant-amplitude test results are presented in table III. Variable-amplitude test results are presented in tables IV and V. Included in the tables and identified by footnotes are the data taken from reference 3, which have been used with new data to establish whether the variations investigated have an effect on fatigue life. For completeness, tables IV and V also contain the load level at failure, and the specimen life (total cycles). to p. 14

Data Analysis

In references 1 to 3, the test results were reduced to a value of $\sum n/N$ and trends were established on this basis. This method was used because of its simplicity and generally accepted usage. In full-scale evaluation tests, the loads are generally programed to represent a given number of flights or flight hours, and because the variation in $\sum n/N$ does not accurately reflect the variation in fatigue life in specific cases (see subsequent discussion), the test results of this investigation were reduced to an equivalent number of

theoretical flights (hereinafter called flights). The test results were also reduced to values of $\sum n/N$ for completeness.

For random tests in which the GAG cycle was inserted, the number of flights was equal to the number of GAG cycles applied. For random tests without the GAG cycle, the number of flights was determined by dividing the specimen life in cycles by 68 (average number of positive half cycles per flight; see previous discussion). For block tests without GAG cycles, the number of flights was determined by dividing the total number of cycles by 12 (lowest load level omitted; see previous discussion). For block tests with GAG cycles inserted, the number of flights was equal to the sum of the GAG cycles applied and the equivalent flights determined for partial blocks not completed.

For $\sum n/N$ calculations the positive half cycles were assumed to be followed by equal negative half cycles in all cases. This assumption leads to some error in the value of $\sum n/N$ in the random 1/2 cycle tests.

The values of theoretical flights and $\sum n/N$ determined for the variable-amplitude tests are given in tables IV and V. In addition, the values of theoretical flights are presented graphically in figure 4.

In figure 4 each symbol represents the geometric mean of the six tests. The ticks represent the limits of scatter in data obtained from a group of six tests conducted with the same load program.

In order to establish more definitely whether an effect was present, the data were compared statistically, with reference 11 as a guide. Two groups of tests differing only in one variable were used in each comparison. In order to make this statistical analysis, the distribution of flights was assumed to be log normal and a 95-percent confidence level was used. The standard deviations of the logarithms of flights were compared by the "F" test (that is, sample standard deviations are (or are not) significantly different) and the means of the logarithms of flights were compared by the "t" test (that is, sample means are (or are not) significantly different). The results of the "t" tests and the ratio of the geometric means of flights for each comparison of two test groups are presented in tables VI and VII.

In the following discussions, it is implied that the variation in life was significant unless otherwise noted. It should be noted that tables VI and VII can be used to establish trends qualitatively since both the direction of change (ratio of geometric means of flights) and significance of the change ("t" test) are shown for each comparison made.

Program number	Material	Positive half cycles per flight	GAG minimum	Remarks
1	7075 -T6	12	—	Block ; step I omitted
1a		12	$-1/2 S_{1g}$	
2		68	—	Random cycle
2a		68	$-1/2 S_{1g}$	
2b		12	$-1/2 S_{1g}$	step I omitted
2c		68	0	
2d		12	0	step I omitted
2e		6	0	step I omitted
3		68	—	Random 1/2 cycle-restrained
3a		68	$-1/2 S_{1g}$	
4		68	—	Random 1/2 cycle-unrestrained
4a		68	$-1/2 S_{1g}$	
4b		45	$-1/2 S_{1g}$	
5	2024 -T3	68	—	Random cycle
5a		68	$-1/2 S_{1g}$	

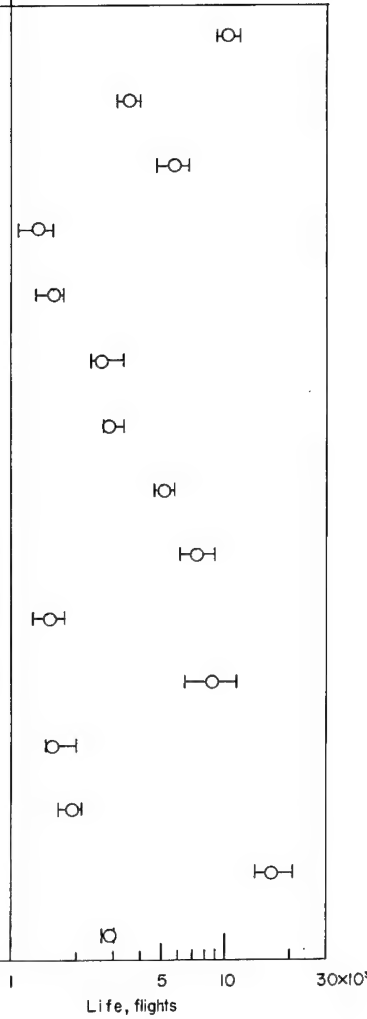


Figure 4.- Results of variable-amplitude fatigue tests. Symbols represent the geometric mean of six tests. Ticks represent scatter limits.

DISCUSSION OF RESULTS

Scatter in Test Data

The scatter in the constant-amplitude tests is well within the normal scatter experienced at the values of life obtained (see table III). The scatter in the variable-amplitude tests seldom exceeded 1.5:1, a trend which is consistent with other variable-amplitude data in this series. (See refs. 1

to 3.) The variations in lives from test group to test group were as high as 4:1 for some comparisons. These variations in life between test groups due to the systematic variations in load programs are not predictable quantitatively and therefore require more detailed study. Furthermore, the variations in life from test group to test group is explained qualitatively in subsequent sections with the aid of residual-stress and residual static-strength considerations. to p. 19

Damage and Failure Considerations

Residual-stress considerations have been used to explain life variations not predicted by analytical approaches. (See refs. 1 to 3.) The variations noted in the present tests can also be explained on the basis of residual stresses, thus further establishing residual-stress effect on fatigue life.

Briefly, the residual-stress conditions assumed are as follows: (See ref. 2 for more detail.) Residual stresses exist upon unloading whenever the local stress at the base of a discontinuity has exceeded the elastic limit of the material. Residual stresses are tensile for compressive loads and compressive for tensile loads. The magnitude of the residual stress is generally not known, although it is known that the value increases as the magnitude of the applied load increases.

The effect of residual stresses on fatigue life is very important. Compressive residual stresses developed in notched fatigue specimens delay fatigue-crack initiation and propagation thus improving fatigue life, whereas tensile residual stresses have the reverse effect. The incremental difference between the highest load level and successive load levels influences the rate at which the effect of the highest load level decays.

Failure of the specimen occurs when the applied load equals the residual static strength of the specimen. It is well known (see ref. 12) that the residual static strength of a specimen first decreases very rapidly as a crack is initiated and then deteriorates further with increasing crack length. However, high loads which produce residual stresses that increase fatigue life by retarding crack initiation and propagation, may also cause early failure of a specimen containing a short fatigue crack if the load exceeds the residual static strength of the specimen. Residual stresses usually have very little, if any, effect on the residual static strength.

Trends in fatigue life observed in the present tests can be explained qualitatively on the basis of changes in residual-stress state at the base of a discontinuity and residual static-strength considerations.

Check Tests

The two sets of data obtained to determine whether the change from semiautomatic loading to automatic loading influenced fatigue life, showed no significant differences (see tables IV and VI).

The series of tests conducted to determine whether or not the method used to generate the random sequences used in this investigation actually produced load programs which were random did not produce a significant variation in life for tests using the same load program but starting on (1) card 1, (2) card 500, (3) card 1000, or (4) card 1500 (see tables IV and VI). It should be noted that the highest load level occurred only in tests which were started on card 1000. For this set of tests the crack length at the time the highest load level was applied had propagated to a length which caused the highest load level to be critical from a residual-strength standpoint; that is, half of the specimens failed during the application of the highest load.

The series of tests which were conducted to evaluate the effect of the location of infrequently occurring high loads within the test program did not produce a significant variation in life. (See tables IV and VI.) Although a significant variation in life was not obtained in this series of tests, it should be noted that there is a slight but consistent trend to shorter life as the location of the highest load approached the nominal life of the specimen. This trend would probably have been much sharper if the ground-air-ground cycles had not been included in the load program (that is, the severe effect of the ground-air-ground cycles tend to overshadow other effects; see subsequent discussions). It is also of interest to note that when the highest load was applied on card 1445 the fatigue crack had obtained a length which made the highest load level critical, similar to tests for program randomness. For tests with the highest load on card 1800 all of the tests failed before this card was reached.

Effect of Load Randomization

The manner in which a given load spectrum is represented (sequence of 1/2 cycles) can cause an appreciable effect on the fatigue life. In this investigation, four sets of tests, each using the same eight load amplitudes and relative frequencies of occurrence to approximate a gust-load spectrum, were conducted by using four possible methods of load sequencing (see previous discussion on load programs). The results of these four sets of tests are shown schematically in figure 5. In figure 5 the symbols represent the geometric mean of six tests, the scatter band ticks have been omitted for clarity. (See table V and fig. 4.) As can be seen in figure 5, the life obtained in the random tests is approximately 45, 30, and 17 percent shorter than in the block tests.

These variations in life between random tests and block tests can be explained on the basis of residual-stress state at the base of the discontinuity. In the block tests, residual stresses formed during the application of high loads are acted on by large groups of cycles of discrete amplitudes until the cumulative combination of amplitude and number of cycles has caused the beneficial effect of the residual stress to decay so that the crack initiation or propagation process becomes active. Depending on the order in which the subsequent groups of cycles are applied, the contribution to actual fatigue damage of many groups of cycles may be negligible. (See, for example, variable-amplitude effect on crack propagation (ref. 13).) In the case of tests using random programs, the amplitude-frequency combination required to overcome the

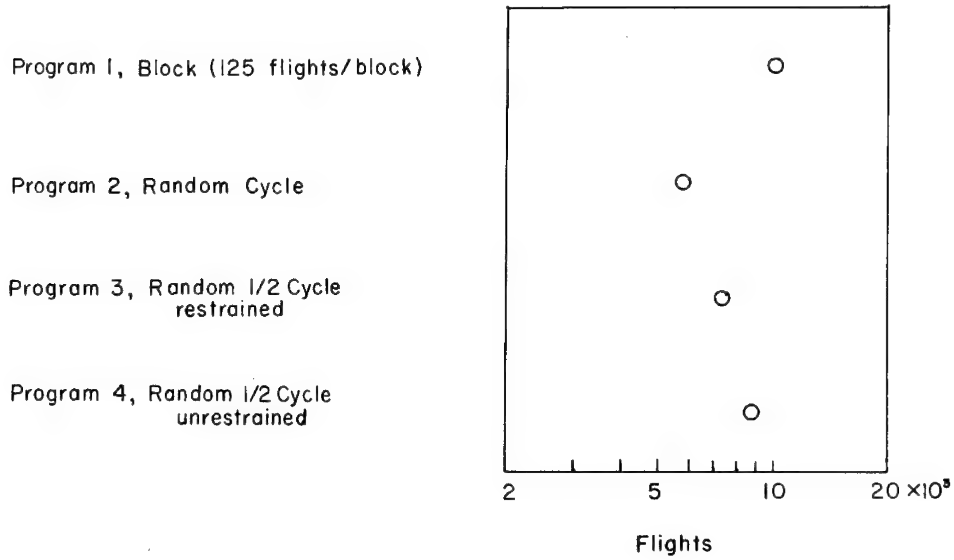


Figure 5.- Results of variable-amplitude fatigue tests showing effect of load randomization using gust loads only. Symbols represent geometric mean of six tests.

beneficial effects of the high load can occur much more frequently in a given interval of time thus permitting the lower amplitude loads to contribute actual fatigue damage.

An examination of each of the three random sequences shows that on the average the range (difference between positive peak and the following negative peak) of each cycle decreases in the following order: (1) random cycle; (2) random half cycle, restrained; and (3) random half cycle, unrestrained. In crack propagation tests, reported in reference 13, the delay in crack propagation at a lower stress after initial propagation at a higher stress, was found to increase as the difference between the high stress and low stress increased. This delay was explained on the basis of residual stresses, that is, the beneficial effect of residual stresses formed while cycling at the high stress decayed at a lower rate as the difference between stresses increased. This effect is expected to be present in variable-amplitude tests using several levels. It also is well known that constant-amplitude fatigue life increases as alternating stress (and therefore stress range) decreases. It therefore follows that the variations in life noted between tests using random sequences is a result of the combined effects of decreased amplitudes and of decreased rate of decay of beneficial residual stress due to the reduced range.

Effect of Inserting Ground-Air-Ground Cycles

The effect on fatigue life of inserting ground-air-ground cycles was evaluated for a variety of conditions. Figure 6 presents the results of several sets of data. As in figure 5 the ticks have been omitted for clarity. As can be seen in figure 6, the insertion of the GAG cycle $\left(R_{GAG} = -1/2\right)$ produces a

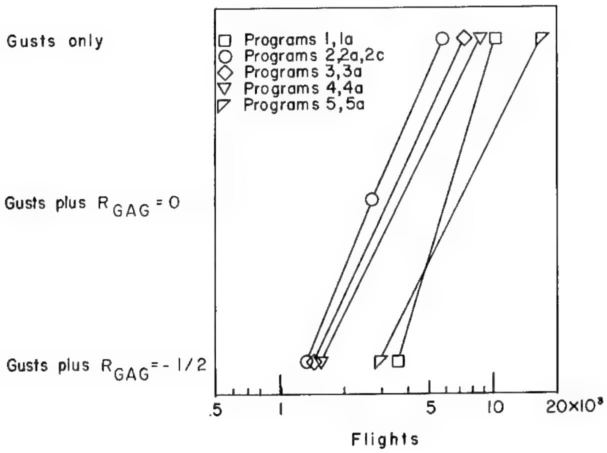


Figure 6.- Results of variable-amplitude fatigue tests showing effect of ground-air-ground cycle. Symbols represent geometric mean of six tests.

reduction in life of approximately 60 percent for block tests and approximately 80 percent for several combinations of random sequence tests and materials (see tables V and VII and fig. 4). The corresponding values of $\sum n/N$ were also reduced proportionately, thus, GAG cycles are much more damaging than anticipated by simple theory. Further, $\sum n/N$ changed from a value greater than 1 to a value less than 1.

The very significant reduction in life with the insertion of ground-air-ground cycles is directly attributable to the change in residual stresses at the base of the discontinuity. The residual stress at the base of the discontinuity is either reduced in magnitude or is reversed in nature (that is, compressive to tensile) depending on the magnitude of the GAG cycle. In either case the succeeding cycles will contribute damage at a much greater rate than in the case when GAG cycles were not applied. The difference in amount of reduction in the block tests as compared with random tests is a function of GAG cycle spacing. That is, in the random sequence tests, the GAG cycles were spaced approximately every 68 positive gust-load cycles, whereas in the block tests the GAG cycles were applied in groups of 125 cycles at the end of each block. Obviously, if the primary contribution of the GAG cycle is to destroy beneficial residual stresses, the greater the dispersion of the GAG cycles throughout the test the greater the effect. Also of interest in this series of tests is the reduction in scatter in tests containing the GAG cycle, that is, for tests without the GAG cycle, the variation in life due to load randomization is approximately 35 percent whereas with the GAG cycle inserted the same comparison yields a variation of approximately 12 percent. (See table V.)

As was noted earlier the magnitude of the GAG cycle determines how much the residual stress is changed. In figure 6, test results are shown for a series of tests with GAG cycle ranges of 0, S_{1g} to 0, and S_{1g} to $-1/2S_{1g}$. As can be seen the life decreases as GAG cycle range increases. It is probable that the effect of the GAG cycle range, S_{1g} to 0, was to reduce the beneficial residual stress, whereas the effect of the GAG cycle range, S_{1g} to $-1/2S_{1g}$, was to reduce the residual stress further and possibly to reverse its direction from compression to tension.

Effect of Omitting Small-Amplitude Loads

In reference 3, the results of a large number of tests indicated that the lowest load level (below the fatigue limit) in eight-step load schedules had essentially no effect on the fatigue life $\left(\sum n/N\right)$. This lack of an effect was attributed to the small-amplitude loads involved and to residual-stress effects. In the present investigation the residual-stress condition was grossly different in tests including GAG cycles and to some extent in random tests. However, the results obtained in the present investigation also indicate that omitting small-amplitude loads did not have a significant effect on the fatigue life. (See results of tests using programs 2(a), 2(b), and also 2(c) and 2(d) in fig. 4 and tables V and VII.)

Effect of Ground-Air-Ground Cycle Spacing

The tests designed to evaluate the effect on fatigue life of the relative frequency of occurrence of the GAG cycle produced two results depending on whether the results were compared on the basis of values of $\sum n/N$ or on the number of flights. (See results of tests using programs 2(d) and 2(e) and also 4(a) and 4(b) in tables V and VII and fig. 4.) In the first comparison $\left(\text{using } \sum n/N\right)$ no effect was noted, whereas in the second comparison a variation of approximately 2:1 and 1.25:1 were obtained, respectively. Sufficient data are not available to establish reliable relationships between GAG cycle spacing and life. From this it appears that the number of gust cycles used to represent typical flight directly influences the results obtained when the number of flights simulated is used as the basis of comparison. Thus, the life obtained in fatigue-evaluation tests can be very misleading if the anticipated service load history is appreciably different from the actual service load history.

CONCLUSIONS

The results of variable-amplitude axial-load fatigue tests on edge notched specimens with loads programed to approximate a gust-load spectrum support the following conclusions:

1. The insertion of ground-air-ground cycles (GAG) produced a large decrease in the number of simulated flights when compared with similar tests without the ground-air-ground cycle. The number of flights simulated was found to be influenced as indicated by the following conditions: (a) GAG cycle range -- number of flights decreased as GAG range increased (the change is much

greater than anticipated by $\sum n/N$) and (b) degree of load randomization - the decrease in number of flights was greater in random tests than in block tests having GAG cycles with the same range.

2. Ground-air-ground cycle spacing has a definite influence on the fatigue life as measured by the number of flights simulated, whereas no effect was noted on the basis of summation of cycle ratios $\sum n/N$.

3. In tests using random-load sequences, the degree of load randomization present influences the fatigue life; life increases as the degree of the randomization increases.

4. The omission of the lowest load level did not significantly affect the number of flights simulated for tests in which the GAG cycle was introduced.

5. All the trends noted herein can be explained qualitatively by using the concepts of residual stresses and residual-static strength.

end

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., July 9, 1964.

APPENDIX

CONVERSION OF U.S. CUSTOMARY UNITS TO SI UNITS

The International System of Units (SI) was adopted by the Eleventh General Conference on Weights and Measures, Paris, October 1960, in Resolution No. 12 (ref. 4). Conversion factors required for units used herein are:

Length: inches $\times$ 0.0254 = Meters (m)

Force: pounds $\times$ 4.4482216 = Newtons (N)

Time: minutes $\times$ 60 = Seconds (s)

Frequency: cps = Hertz (Hz)

Prefixes to indicate multiples of units are:

10^{6} mega (M)

10^{-3} milli (m)

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TABLE I.- TENSILE PROPERTIES OF ALUMINUM-ALLOY MATERIALS TESTED

[Data from ref. 7]

Property	Average	Minimum	Maximum
7075-T6 (152 tests)			
Yield stress (0.2-percent offset) -			
In ksi	75.50	71.54	79.79
In MN/m^2	520.2	492.9	549.8
Ultimate tensile strength -			
In ksi	82.94	79.84	84.54
In MN/m^2	571.5	550.1	582.5
Total elongation (2-inch (5.08-cm) gage length), percent	12.3	7.0	15.0
2024-T3 (147 tests)			
Yield stress (0.2-percent offset) -			
In ksi	52.05	46.88	59.28
In MN/m^2	358.6	323.0	408.4
Ultimate tensile strength -			
In ksi	72.14	70.27	73.44
In MN/m^2	497.0	484.2	506.0
Total elongation (2-inch(5.08-cm) gage length), percent	21.6	15.0	25.0

TABLE II.- VARIABLE-AMPLITUDE LOAD PROGRAMS

APPROXIMATING A GUST-LOAD HISTORY

7075-T6 aluminum-alloy specimens; S_{1g} = 20 ksi (137.8 MN/m^2)				
Load level	Representative stress - ksi	Representative stress - MN/m^2	Relative frequency, cycles	n/N per cycle
1	21.5	148.4	42.000	0
2	25.3	174.6	7,500	.00000625
3	28.7	198.0	1,190	.00006024
4	32.6	224.9	175	.00017241
5	36.3	250.5	23	.00034482
6	40.1	276.7	2.5	.00067120
7	43.9	302.9	.5	.00122000
8	47.5	327.8	.1	.00208000
R_{GAG} = 0; GAG cycle S_{1g} to 0 (20 ksi to 0) (137.8 MN/m^2 to 0)				.00002000
R_{GAG} = -1/2; GAG cycle S_{1g} to -1/2S_{1g} (20 ksi to -10 ksi) (137.8 MN/m^2 to -68.9 MN/m^2).				.00006293
2024-T3 aluminum-alloy specimens; S_{1g} = 17.4 ksi (119.9 MN/m^2)				
1	19.5	134.4	82,000	0
2	22.5	155.0	15,000	.00000111
3	25.6	176.4	2,800	.00001370
4	28.7	197.7	350	.00005411
5	31.9	219.8	46	.00015391
6	35.1	241.8	7.4	.00036216
7	38.4	264.6	1.6	.00075500
8	41.5	285.9	.35	.00013314
R_{GAG} = -1/2; GAG cycle S_{1g} to -1/2S_{1g} (17.4 ksi to -8.7 ksi) (119.9 MN/m^2 to -59.9 MN/m^2)				.00002325

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TABLE III.- RESULTS OF CONSTANT-AMPLITUDE FATIGUE TESTS

(a) 2024-T3 aluminum alloy

[S_{mean} = 4.35 ksi (29.97 MN/m^2); S_{max} = 17.4 ksi (119.9 MN/m^2)]

Specimen	Life, cycles
A31N2-6	53,000
A31N2-8	52,000
A31N2-2	49,000
A31N2-10	40,000
A31N2-4	39,000
A31N2-9	30,000
Geometric mean . . .	43,000

(b) 7075-T6 aluminum alloy

[S_{mean} = 5 ksi (34.4 MN/m^2); S_{max} = 20 ksi (137.8 MN/m^2)]

Specimen	Life, cycles
B93N2-6	20,570
B93N2-1	15,650
B86N2-8	15,530
B86N2-3	15,090
B103N2-7	13,430
Geometric mean . . .	15,890

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TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

ON 7075-T6 ALUMINUM-ALLOY SPECIMEN

[S_{1g} = 20 ksi (137.8 MN/m^2)]

(a) Block tests to evaluate possible machine difference

Specimen	Load level at failure	Life, cycles	$\sum$ n/N	Flights
Semiautomatic loading; step 1 omitted; reference 3				
B110N1-1	3	142,120	2.54	11,843
B103N1-9	8	125,690	2.36	10,474
B110N1-2	2	121,450	2.20	10,121
B103N1-3	3	114,450	1.98	9,537
B103N1-2	7	99,170	1.85	8,264
B101N1-2	3	97,380	1.71	8,115
Geometric mean		115,700	2.09	9,641
Automatic loading; same as reference 3				
B132N2-6	4	140,900	2.54	11,742
B126N2-4	2	123,035	2.21	10,253
B104N2-5	7	115,759	2.10	9,647
B124N2-5	7	115,759	2.10	9,647
B137N2-6	6	115,560	2.06	9,630
B131N2-5	3	115,111	2.01	9,593
Geometric mean		120,600	2.15	10,058

TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

ON 7075-T6 ALUMINUM-ALLOY SPECIMEN - Continued

(b) Random cycle tests to evaluate randomness of random sequence generation method*

Specimen	Load level at failure	Life, cycles	$\sum n/N$	Flights
Start at card 1				
B9N2-3	4	19,890	0.43	1,515
B12N2-3	2	19,550	.42	1,489
B9N2-6	2	15,232	.33	1,162
B8N2-5	4	13,498	.29	1,031
B14N2-7	4	12,410	.27	945
B9N2-9	4	12,376	.27	942
Geometric mean		15,170	0.33	1,158
Start at card 500				
B129N2-5	5	19,788	0.43	1,498
B1N2-7	4	19,312	.42	1,466
B132N2-10	5	19,108	.42	1,451
B129N2-10	4	15,470	.34	1,173
B128N2-1	5	15,300	.33	1,160
B9N2-7	5	13,974	.30	1,057
B10N2-3	6	13,498	.29	1,023
Geometric mean		16,450	0.36	1,256
Start at card 1000				
B13N2-7	7	17,631	0.28	1,369
B5N2-4	4	14,926	.32	1,122
B4N2-8	8	14,756	.32	1,109
B123N2-10	8	14,756	.32	1,109
B128N2-3	8	14,756	.32	1,109
B128N2-8	6	14,722	.32	1,108
Geometric mean		15,225	0.33	1,162
Start at card 1500				
B4N2-9	6	20,842	0.45	1,592
B1N2-1	4	20,196	.43	1,544
B8N2-9	4	18,258	.39	1,394
B4N2-6	7	14,212	.31	1,087
B8N2-9	7	14,212	.31	1,087
B1N2-9	4	13,940	.30	1,066
Geometric mean		16,670	0.36	1,272

*Highest load level occurs on card 1435.

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TABLE IV.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

ON 7075-T6 ALUMINUM-ALLOY SPECIMEN - Concluded

(c) Block tests plus $R_{GAG} = -1/2$ to evaluate effect of highest load level location within test program

Specimen	Load level at failure	Life, cycles	$\sum$ n/N	Flights
Load 8 on card 1				
B127N2-5	5	63,494	1.36	4,884
B131N2-8	6	57,709	1.23	4,439
B122N2-9	6	57,709	1.23	4,439
B128N2-2	2	52,379	1.13	4,029
B108N2-4	6	52,345	1.13	4,029
B124N2-2	5	42,280	.90	3,252
Geometric mean		53,900	1.16	4,146
Load 8 on card 250				
B17N2-3	2	56,202	1.17	4,323
B15N2-2	4	51,675	1.09	3,975
B13N2-5	7	48,055	1.02	3,697
B18N2-10	7	48,055	1.02	3,697
B16N2-7	5	46,092	.98	3,546
B17N2-4	3	44,392	.96	3,415
Geometric mean		48,930	1.04	3,764
Load 8 on card 700				
B122N2-5	6	57.709	1.23	4,439
B127N2-10	6	57,709	1.23	4,439
B123N2-3	6	52,345	1.13	4,029
B126N2-10	7	48,055	1.03	3,697
B122N2-3	7	48,055	1.03	3,697
B5N2-7	4	40,103	.84	3,085
B126N2-2	6	38,423	.82	2,956
Geometric mean		48,380	1.04	3,922
Load 8 on card 1445				
B101N2-4	6	52,345	1.13	4,029
B104N2-2	8	48,025	1.02	3,694
B128N2-9	8	48,025	1.02	3,694
B104N2-10	5	46,125	.98	3,548
B122N2-4	5	46,125	.98	3,548
B129N2-4	6	40,501	.87	3,115
Geometric mean		46,720	1.00	3,594
Load 8 on card 1800				
B131N2-1	3	55,997	1.20	4,306
B124N2-10	6	52,344	1.13	4,026
B10N2-2	7	48,056	1.02	3,697
B123N2-4	3	36,381	.77	2,798
B132N2-5	4	34,554	.73	2,658
B128N2-10	5	30,926	.67	2,379
Geometric mean		41,990	.98	3,230

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TABLE V.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

USING GUST-LOAD SPECTRUM

(a) 7075-T6 aluminum-alloy specimens; S_{1g} = 20 ksi (137.8 MN/m^2)

Specimen	Load level at failure	Life, cycles	$\sum$ n/N	Flights
Program 1: Block tests; 125 flight/block; step 1 omitted				
B123N2-9	6	142,289	2.56	11,857
B129N2-1	7	131,649	2.37	10,970
B104N2-7	7	131,649	2.37	10,970
B124N2-7	5	131,617	2.36	10,968
B123N2-3	5	115,598	2.07	9,633
B104N2-3	6	108,529	1.96	9,044
Geometric mean		120,600	2.27	10,050
Program 1(a): Program 1 plus 125 GAG/block; R_{GAG} = -1/2				
B101N2-4	6	52,346	1.13	4,027
B104N2-2	8	48,025	1.02	3,694
B128N2-9	8	48,025	1.02	3,694
B104N2-10	5	46,125	.98	3,548
B122N2-4	5	46,125	.98	3,548
B129N2-4	6	40,501	.87	3,115
Geometric mean		46,720	1.00	3,594
Program 2: Random cycle; 68 positive half cycles/flight				
B83N2-9	8	460,595	1.50	6,773
B86N2-4	4	431,695	1.40	6,348
B103N2-8	6	404,903	1.32	5,954
B83N2-3	7	397,083	1.29	5,839
B93N2-3	6	371,651	1.21	5,465
B100N2-2	5	321,977	1.05	4,735
Geometric mean		395,500	1.29	5,815
Program 2(a): Program 2 plus GAG/68 positive half cycles; R_{GAG} = -1/2				
B93N2-5	5	106,846	0.43	1,548
B86N2-1	4	102,431	.42	1,485
B92N2-3	5	96,946	.40	1,406
B113N2-9	4	89,389	.37	1,295
B113N2-5	4	87,457	.37	1,267
B93N2-4	4	73,209	.30	1,061
Geometric mean		94,020	0.38	1,334

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TABLE V.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

USING GUST-LOAD SPECTRUM - Continued

(a) 7075-T6 aluminum-alloy specimens; S_{1g} = 20 ksi (137.8 MN/m^2) - Continued

Specimen	Load level at failure	Life, cycles	$\sum n/N$	Flights
Program 2(b): Program 2 plus GAG/12 positive half cycles; step 1 omitted; $R_{GAG} = -1/2$				
B130N2-7	5	22,848	0.49	1,744
B104N2-9	5	22,202	.48	1,697
B130N2-1	5	20,604	.44	1,571
B104N2-8	4	20,604	.44	1,571
B130N2-6	4	19,074	.41	1,454
B104N2-6	4	16,944	.37	1,292
Geometric mean		20,300	0.44	1,547
Program 2(c): Program 2 plus GAG/68 positive half cycles; $R_{GAG} = 0$				
B113N2-3	6	229,632	0.81	3,328
B113N2-10	6	198,202	.70	2,873
B93N2-2	6	198,202	.70	2,873
B86N2-10	6	172,914	.61	2,506
B103N2-3	5	167,049	.58	2,421
B115N2-8	6	159,976	.56	2,318
Geometric mean		186,300	0.65	2,699
Program 2(d): Program 2 plus GAG/12 positive half cycles; step 1 omitted; $R_{GAG} = -1/2$				
B130N2-8	6	43,826	0.81	3,329
B130N2-5	2	39,066	.72	2,970
B131N2-4	6	37,774	.70	2,874
B132N2-2	5	36,414	.67	2,770
B124N2-3	5	35,530	.65	2,705
B131N2-9	5	35,530	.65	2,705
Geometric mean		37,970	0.70	2,884
Program 2(e): Program 2 plus GAG/6 positive half cycles; step 1 omitted; $R_{GAG} = 0$				
B93N2-9	6	40,766	0.76	5,823
B113N2-4	6	40,698	.75	5,814
B113N2-1	5	36,822	.68	5,260
B113N2-7	6	35,495	.66	5,075
B93N2-7	5	33,660	.62	4,808
B86N2-7	6	32,470	.60	4,638
Geometric mean		36,510	0.68	5,217

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TABLE V.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

USING GUST-LOAD SPECTRUM - Continued

(a) 7075-T6 aluminum-alloy specimens; S_{1g} = 20 ksi (137.8 MN/m^2) - Concluded

Specimen	Load level at failure	Life, cycles	$\sum$ n/N	Flights
Program 3: Random half cycle, restrained; 68 positive half cycles/flight				
B83N2-6	7	582,111	1.89	8,910
B86N2-6	5	532,165	1.73	7,826
B110N1-6	6	496,805	1.62	7,306
B86N2-2	6	495,207	1.61	7,282
B103N2-6	5	480,100	1.56	7,060
B93N2-8	5	451,075	1.47	6,060
Geometric mean		504,700	1.64	7,358
Program 3(a): Program 3 plus GAG/68 positive half cycles; R_{GAG} = -1/2				
B103N2-5	5	119,000	0.48	1,773
B93N2-10	4	115,606	.47	1,672
B113N2-10	4	107,987	.44	1,566
B103N2-4	4	100,775	.41	1,461
B86N2-9	4	99,567	.41	1,443
B103N2-1	4	87,458	.36	1,268
Geometric mean		105,800	0.43	1,515
Program 4: Random half cycle, unrestrained; 68 positive half cycles/flight				
B17N2-8	8	763,099	2.33	11,222
B9N2-5	8	655,373	2.03	9,638
B8N2-10	8	655,373	2.03	9,638
B5N2-10	8	655,373	2.03	9,638
B16N2-1	8	478,873	1.34	6,454
B11N2-2	8	478,873	1.34	6,454
Geometric mean		598,300	1.81	8,798
Program 4(a): Program 4 plus GAG/68 positive half cycles; R_{GAG} = -1/2				
B51N2-1	4	140,023	0.55	2,029
B51N2-10	5	121,733	.48	1,764
B5N2-8	8	100,576	.39	1,457
B52N2-10	8	100,576	.39	1,457
B51N2-2	8	100,576	.39	1,457
B51N2-9	8	100,576	.39	1,457
Geometric mean		109,600	0.43	1,588
Program 4(b): Program 4 plus GAG/45 positive half cycles; R_{GAG} = -1/2				
B12N2-4	8	101,310	0.44	2,179
B12N2-5	5	95,878	.42	2.062
B11N2-1	4	93,033	.40	2,000
B9N2-2	2	91,878	.39	1,976
B6N2-3	5	84,780	.36	1,823
B16N2-4	5	76,923	.33	1,654
Geometric mean		90,400	0.39	1,942

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57618

A1

TABLE V.- RESULTS OF VARIABLE-AMPLITUDE FATIGUE TESTS

USING GUST-LOAD SPECTRUM - Concluded

(b) 2024-T3 aluminum-alloy specimens; S_{mean} = 17.4 ksi (119.9 MN/m^2)

Specimen	Load level at failure	Life, cycles	$\sum$ n/N	Flights
Program 5: Random cycle; 68 positive half cycles/flight				
A108N2-4	8	1,400,460	1.18	20,595
A33N2-3	8	1,259,784	1.06	18,840
A100N2-4	5	1,242,870	1.05	18,277
A109N2-4	4	997,016	.85	14,662
A84N2-1	5	941,196	.80	13,841
A33N2-4	5	932,346	.79	13,711
Geometric mean		1,110,000	0.94	16,439
Program 5(a): Program 5 plus GAG/68 positive half cycles; R_{GAG} = -1/2				
A80N2-1	7	205,594	0.24	2,978
A78N2-5	8	200,997	.23	2,913
A81N2-4	8	200,997	.23	2,913
A80N2-6	3	193,096	.23	2,798
A81N2-1	4	191,682	.22	2,778
A79N2-2	6	183,471	.21	2,659
Geometric mean		195,800	0.23	2,837

TABLE VI.- RESULTS OF STATISTICAL ANALYSIS OF CHECK TEST DATA

Side group \ Top group	Semiautomatic	Automatic	Start card 1	Start card 500	Start card 1000	Start card 1500	Load 8 on card 1	Load 8 on card 250	Load 8 on card 700	Load 8 on card 1445	Load 8 on card 1800
Semiautomatic		No									
Automatic	0.96										
Start card 1				No	No	No					
Start card 500			0.92		No	No					
Start card 1000			0.99	1.18		No					
Start card 1500			0.91	0.99	0.92						
Load 8 on card 1								No	No	No	No
Load 8 on card 250							1.10		No	No	No
Load 8 on card 700							1.11	1.00		No	No
Load 8 on card 1445							1.15	1.05	1.04		No
Load 8 on card 1800							1.28	1.16	1.15	1.11	

	No
0.96	

No — Sample flight geometric means are significantly different.

0.96 — Ratio of sample flight geometric means $\frac{\text{Top group}}{\text{Side group}}$.

TABLE VII.- RESULTS OF STATISTICAL ANALYSIS OF VARIABLE-AMPLITUDE FATIGUE TESTS

Side group \ Top group, Condition	1	1(a)	2	2(a)	2(b)	2(c)	2(d)	2(e)	3	3(a)	4	4(a)	4(b)	5	5(a)
Program 1		Yes	Yes	----	----	----	----	---	Yes	----	Yes	----	---	----	---
Program 1(a)	2.78		----	Yes	Yes	----	----	---	----	Yes	----	Yes	---	----	---
Program 2	1.72	----		Yes	----	Yes	----	---	Yes	----	Yes	----	---	----	---
Program 2(a)	----	2.69	4.36		No	Yes	----	---	----	Yes	----	Yes	---	----	---
Program 2(b)	----	2.32	----	0.87		----	Yes	---	----	----	----	----	---	----	---
Program 2(c)	----	2.16		0.50	----		No	---	----	----	----	----	---	----	---
Program 2(d)	----	----	----	----	0.54	0.93		Yes	----	----	----	----	---	----	---
Program 2(e)	----	----	----	----	----	----	0.55		----	----	----	----	---	----	---
Program 3	1.36	----	0.79	----	----	----	----	---		Yes	Yes	----	---	----	---
Program 3(a)	----	2.37	----	0.88	----	----	----	---	4.86		----	No	---	----	---
Program 4	1.14	----	0.66	----	----	----	----	---	0.84	----		Yes	---	----	---
Program 4(a)	----	1.85	----	0.84	----	----	----	---	----	0.95	5.54		Yes	----	---
Program 4(b)	----	----	----	----	----	----	----	---	----	----	----	0.82		----	---
Program 5	----	----	----	----	----	----	----	---	----	----	----	----	----		Yes
Program 5(a)	----	----	----	----	----	----	----	---	----	----	----	----	----	5.80	

	Yes
1.28	

Yes — Sample flight geometric means are significantly different.

1.28 — Ratio flight geometric means, $\frac{\text{Top group}}{\text{Side group}}$.

NASA-Langley, 1964 L-3567

NASA TN D-1584
National Aeronautics and Space Administration.
EVALUATION OF THE INFLUENCE OF LOAD RANDOMIZATION AND OF GROUND-AIR-GROUND CYCLES ON FATIGUE LIFE. Eugene C. Naumann. October 1964. 34p. OTS price, $1.00.
(NASA TECHNICAL NOTE D-1584)

Variable-amplitude axial-load fatigue tests were conducted on 2024-T3 and 7075-T6 aluminum-alloy edge notched sheet specimens having a theoretical elastic stress concentration factor of 4. Load programs were designed to simulate a gust-load history with and without ground-air-ground cycles. Fatigue life was found to decrease sharply with the introduction of ground-air-ground cycles with the decrease being influenced by ground-air-ground cycle range, relative frequency of occurrence of the ground-air-ground cycle, and by the degree of load randomization present in the test. A new programed variable-amplitude axial-load fatigue machine is described.

I. Naumann, Eugene C.
II. NASA TN D-1584

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